AN ENERGY PUMPING FREQUENCY INCREASED VIBRATION ENERGY HARVESTER

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Abstract: This paper reports the design, fabrication, and testing of an electromagnetic vibration energy harvester that utilizes a novel method of energy pumping based frequency upconversion. The proposed harvester gets benefit from the resonance amplification phenomenon, at multiple frequencies. When excited at the third order resonance frequency of 10.3 Hz with a peak acceleration of 1g, the reported harvester generates a peak-to-peak voltage of 15.4 V and RMS voltage of 3.88 V across an optimal load of 3 kΩ and delivers a peak power of 20.9 mW and an average power of 5.02 mW. The harvester is capable of harvesting a useful amount of power (26 µW) from as low acceleration as 50 mg, and able to work at unpredictably high acceleration levels (1g).

Keywords: Energy Harvesting, Energy Pumping, Frequency Upconversion, Wideband Harvester

INTRODUCTION

In recent years there has been an increasing research interest in powering micromachined wireless sensors by harvesting energy from their environment. Among the renewable energy source, vibration energy has attracted particular interest due to its abundance in target environments of wireless sensor networks [1]. However, very little effort has been made in harvesting energy from most commonly occurring harmonics of very low frequency (<20 Hz). Energy harvesting in a low frequency environment is associated with many challenges such as reduced power flow into the harvester, large amplitude of the seismic mass oscillation, and requirement of high electromechanical coupling coefficient. To meet these challenges, various methods of mechanical frequency upconversion have been developed [2]. However, these methods rely on the self sustained transient oscillation of the high frequency oscillator, and hence the high frequency oscillator cannot get benefit from resonance amplification. In fact, in conventional frequency upconversion methods, motion of the high frequency oscillator is intervened by the low frequency oscillator during the energy transfer process and any unexhausted energy of the former is wasted.

In this paper we present an energy pumping based frequency upconversion method, whereby energy is pumped from a low frequency oscillator to a high frequency oscillator in the form of pulses. The energy of the high frequency oscillator is then transferred to electrical domain. The uninterrupted energy transfer mechanism, from the low frequency oscillator to the high frequency oscillator, allows the latter to exhibit resonance amplification at multiple frequencies.

DESIGN AND FABRICATION

Fig. 1 shows the design of the proposed harvester. A disc shaped pickup coil of radius 11.5 mm and thickness 3.5 mm is formed by hand-winding an enameled copper wire of diameter 100 µm on an acrylic bobbin. The coil is then anchored with an acrylic platform by means of a PVC beam of length 10 mm, width 10 mm and thickness 0.8 mm. The beam and coil arrangement acts as a high frequency resonator whose resonance frequency is found 32.9 Hz by finite element modeling. The mass and resistance of the coil are measured to be 6 g and 160 Ω, respectively. The total and effective length of the coil is analytically estimated to be 74.76 m and 23.8 m respectively. To form a closed magnetic field linking the coil, four NdFeB magnets (25 mm × 5 mm × 3 mm) with residual flux density of 1.2 T are attached with the aforementioned platform, using a mild steel keeper of thickness 1 mm on each side, as shown in Fig. 2(b). The coil and magnet assembly, measured to be 47 g, is then anchored with the harvester casing by means of two PVC beams having length, width and thickness of 31 mm, 4 mm and 0.5

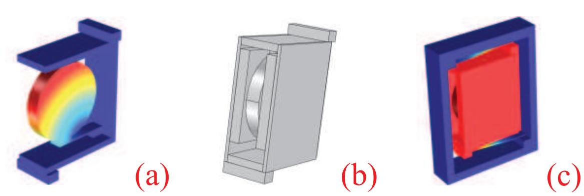


Fig. 1: Schematic design of the device, (a) inner structure showing the high frequency oscillators, (b) magnetic arrangement and (c) the complete harvester.

mm respectively, as shown in Fig. 1(c). This arrangement constituted a low frequency resonator whose resonance frequency is found to be 10 Hz by FEM. A finite clearance is provided between the magnetic assembly and the casing of the harvester. The casing of the harvester is machined out of a 13 mm acrylic plate using pulse laser machining technique. It has an outer width, length and wall thickness of 45 mm, 60 mm and 3 mm, respectively. The Fabricated harvester has an internal volume of 27.38 cm^3 (35 cm^3 including outer casing).

In response to an external low frequency vibration, the low frequency oscillator, containing the coil and the magnetic assembly as proof mass, resonates. During this low frequency oscillation the coil and magnets move collectively and no energy is transferred to the electrical domain. The decreased damping ratio due to absence of the electrical damping, and increased proof mass due to combined effect of the coil and the magnets result in an increased energy flow into the harvester [3]. When the amplitude of this low frequency oscillation becomes greater than the clearance provided for free oscillation, the magnetic assembly collides with the harvester casing. During this mechanical impact, an amplified velocity reversing acceleration acts on the magnet and coil assembly and energy is pumped to the high frequency resonator. As this impulsive energy transfer occurs each time the low frequency resonator collides with the base of the harvester, the high frequency resonator comes into a state of impulse driven resonance. The high frequency oscillator shows resonance amplifications for the frequencies of the external vibrations satisfying the relation $f_{high} = nf_{low}$; where n is an integer showing the order of the resonance. During the vibration of the high frequency oscillator, the magnetic flux linking the coil changes and energy flows to the electrical domain.

As the high frequency oscillator is elastically anchored with the low frequency oscillator, the energy of the former tends to go back to the latter. Such an undesirable reverse energy flow is protected by tilting the direction of the fundamental mode degree of freedom of the high frequency resonator at an angle of 60^o as compared to that of the low frequency oscillator.

RESULT AND DISCUSSION

A vibration simulator system by IMV Corporation, Japan is used to characterize the harvester. The aforementioned system provides a software interface on a PC to define test conditions. The test definition is then loaded to a vibration controller unit. The controller unit controls the gain of an amplifier unit based on the test definition and the feedback from a reference accelerometer, mounted on the shaker table along with the harvester. Another pickup coil with a total wire length of 200 m is rigidly mounted near the harvester in such a way that the leakage magnetic flux from the magnetic assembly links the coil. The voltage induced across the aforementioned coil, due to the oscillation of the magnetic assembly is amplified and used to monitor the motion of the low frequency oscillator.

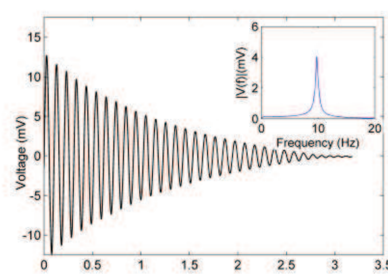
The impulse response of both the high frequency and the low frequency oscillations are used to determine the resonance frequencies and damping characteristics. Fig. 2 shows the open loop impulse response of the low frequency oscillation with the FFT of the signal in the inset. From the impulse response, using the logarithmic decrement method, the damping ratio can determined as

$$\zeta = \frac{\ln(a_1 / a_2)}{\sqrt{(2\pi)^2 + [\ln(a_1 / a_2)]^2}} \tag{1}$$

where a_1 and a_2 are the amplitudes of two consecutive cycles in the impulse response plot. The damping ratio calculated from the open loop impulse response can be considered as the mechanical damping ratio (ζ_m). This consideration is supported by the fact that during open loop operation no energy is transferred to the electrical domain. The damping ratio calculated from the impulse response with an optimal load represents the sum of electrical and mechanical damping ratios (ζ_t). The electrical damping ratio can be determined from ζ_t and ζ_m as,

$$\zeta_e = \zeta_t - \zeta_m \tag{2}$$

The resonance frequency of a resonator can be



Time (s)

Fig. 2: Open loop impulse response of the low the FFT of the signal in the inset.

estimated by taking Discrete Fourier Transform of the impulse response.

Table 1 shows the measured parameters of the harvester. It may be noted that, when the harvester is connected with the load, the quality factor of the high frequency resonator decreases and that of the low frequency resonator increases. A higher loaded quality factor of the low frequency resonator as compared to open loop quality factor is not unexpected. Because, when a load is applied, the quality factor of the high frequency resonator decreases due to electrical damping. With reduced quality factor, the high frequency resonator absorbs less energy from the low frequency resonator, which in-turn causes the energy flowing out of the low frequency resonator to decrease and its quality factor to increase. The increase in the quality factor for the low frequency energy absorbing phase of motion ensures an increased power flow into the device [3].

An optimal load of 3 kΩ is experimentally determined by increasing the load impedance in steps and comparing the power delivered in each step. Fig. 3 shows the voltage obtained across the optimal load at a 10.3 Hz excitation with a peak acceleration of 1g. A peak to peak voltage of 15.4 V and an RMS voltage of 3.88 V are recoded. Pumping of energy after every three cycles, indicating that the high frequency resonator is under 3rd order resonance, is clearly visible.

To investigate the frequency response of the harvester the frequency of the base excitation is given a sweep at a sweep rate of 0.25 Hz/s. The voltage across the load is recorded at a sampling rate of 10 kHz. The recorded waveform is then divided into small windows of length 1s. RMS voltage and average power for each data window is computed and correlated with the frequency. Variation of the average power with frequency, obtained using the aforementioned method, is shown in Fig. 4. Resonance amplification at multiple frequencies can be observed. With a natural frequency of 31 Hz of the high frequency oscillator, the resonance peaks at 15.5, 10.3, 7.75, 6.2 and 5.1 Hz corresponds to 2nd, 3rd, 4th, 5th and 6th order resonances respectively.

Table 1: Parameters of the harvester.

Dynamics	f_o (Hz)	ζ_e	ζ_m	Q_{load}	Q_{open}
Low Freq.	9.76	-0.0015	0.0165	33.3	30.3
High Freq.	31	0.0115	0.0138	19.76	36.2

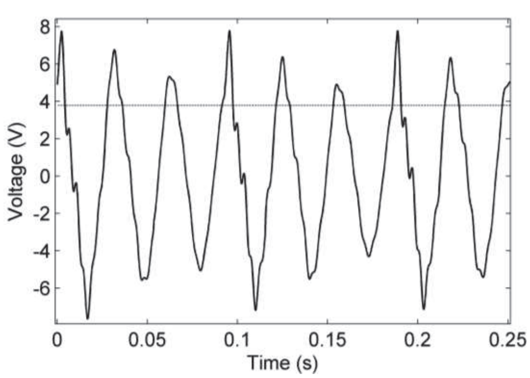


Fig. 3: Voltage across a load of 3 KΩ at 10.3 Hz 1g excitation, the horizontal line shows RMS voltage.

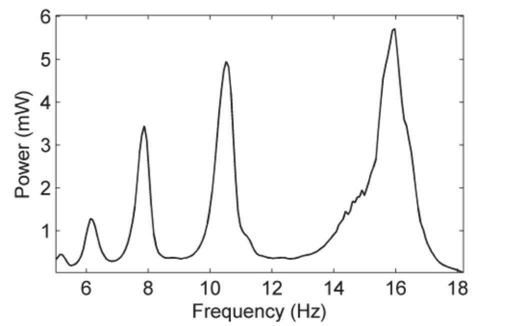


Fig. 4: Variation of average power with frequency at a peak acceleration of 1g.

A straight forward advantage of resonance amplification at multiple frequencies is the improved performance of the harvester for wideband excitation. Secondly, in many scenarios, energy in ambient vibrations is distributed in different harmonics. For example, the vibration in a vertical stabilizer on a PZL SW-4 helicopter occurs with dominant harmonics at 30, 45 and 90 Hz with a peak acceleration value of 15.4, 8.6 and 1.5 m/s^2, respectively [4]. In such a scenario, the energy pumping frequency increased harvester can be used to effectively harvest energy from different harmonics.

The number of resonance peaks in a certain frequency range depends upon the natural frequency of the high frequency resonator, which can be increased to get more number of resonance peaks. The settling time of an oscillator depends upon the effective mass of the resonator [5]. Therefore, an increase in natural frequency of the high frequency resonator, by increasing the spring constant, will increase the order of resonance at a certain frequency without much affecting the average power at that frequency.

Fig. 5 shows variation of the average power with acceleration at 10.3 Hz. At the very low acceleration of 50 mg, allowed by the testing system, a useful power of 26 μW is generated. The average power monotonically increased with frequency to 5.06 mW as the acceleration is increased to the maximum value of 1g allowed by the shaker system.

The volume figure of merit [1] of the proposed harvester is compared with the current state-of-the-art [6–14] in Fig. 6. It can be observed that in the low frequency range, the proposed harvester significantly outperforms other efforts.

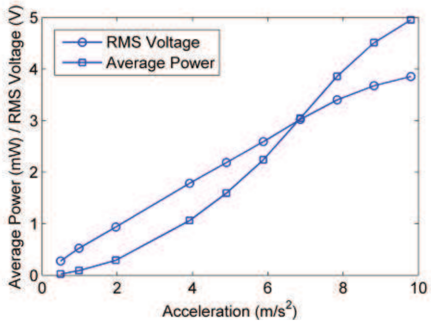


Fig. 5: RMS voltage and power delivered to a load of 3 kΩ at a 10.3 Hz excitation with peak acceleration of 5mg to 1g.

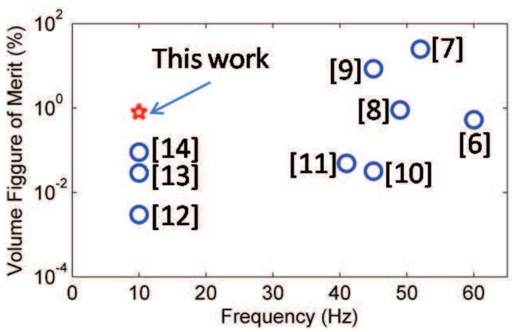


Fig. 6: Comparison of the volume figure of merit of the proposed harvester with the current state-of-the art.

CONCLUSION

A novel technique of energy pumping based frequency upconversion is presented and its effectiveness in harvesting energy from low frequency oscillations is demonstrated. With multiple resonance peaks corresponding to higher order resonances, the proposed harvester can be used to effectively scavenge energy from multiple harmonics, and improved performance is expected for wideband excitations. The average power density of 183.34 $\mu W/cm^3$ and volume figure of merit of 0.83% calculated at 10.3 Hz, 1g, significantly outperformed other efforts made to date to harvest energy from low frequency vibrations (≤20 Hz).

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